The Pionic Contribution to Diffuse Gamma Rays: Upper Limits

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ABSTRACT

Diffuse gamma rays probe the highest-energy processes at the largest scales. Here we derive model-independent constraints on the hadronic contribution to the Galactic and extragalactic γ-ray spectra at in the energy range 50 MeV $\lesssim E_\gamma \lesssim$ 10 GeV. The hadronic component is dominated by emission from neutral pions, with a characteristic spectrum symmetric about $m_{\pi^0}/2$. We exploit the well-defined properties of the pion decay spectrum to quantify the maximum pionic fraction of the observed γ-ray intensity. We find that the Galactic spectrum above 30 MeV can be at most about 50% pionic. The maximum pionic contribution to the extragalactic spectrum is energy dependent; it also depends on the redshift range over which the sources are distributed, ranging from as low as about 20% for pions generated very recently, to as much as 90% if the pions are generated around redshift 10. The implications of these constraints for models of γ-ray and neutrino emission are briefly discussed.

Subject headings: cosmic rays – gamma rays – nuclear reactions, nucleosynthesis, abundances

1. Introduction

The prominence of diffuse emission in the γ-ray sky above $\gtrsim$ 50 MeV has been known since the earliest days of γ-ray astronomy itself (Fichtel, Kniffen, & Hartman 1973). These diffuse photons carry unique and direct information about some of the most energetic sites and processes in nature. Diffuse γ-ray observations thus provide a powerful tool both (1) to test specific models of known or postulated astrophysical sources, and (2) to constrain, in a model-independent way, known physical processes which might occur in one or more sources. We take the latter approach in this paper, focusing in particular on the γ-ray spectrum and the constraints it places on the contribution of hadronic interactions to the overall diffuse background.

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The diffuse γ-ray sky is dominated by emission from the Galactic plane (Hunter et al. 1997), but the presence of emission even at the Galactic poles already suggests that an extragalactic component is present as well (Sreekumar et al. 1998). The spectra of these two components are each remarkable both for what they show and what they do not show. Namely, in neither spectrum is there a strong indication of hadronic interactions, which are dominated by proton collisions with interstellar matter, which yield γ-rays predominantly through pion production and decay: $pp \to pp\pi^0 \to \gamma\gamma$. The pionic spectrum is symmetric about a peak at $m_\pi/2$. This feature, the "pion bump," is notably inconspicuous in the γ-ray data.

As we will see in detail below, the Galactic spectrum is well-described by a simple broken power law, with a break at ~ 0.77 GeV. No strong pion bump is observed. Hunter et al. (1997) do note that there is as a $\sim 2\sigma$ deviation in the $60 - 70$ MeV energy bin, but this region in the spectrum is otherwise well-fit by a smooth power law. If real, this feature is remarkably narrow. Intriguingly, detailed models of known Galactic processes run into difficulties explaining this spectrum (and its simplicity). The model of Strong, Moskalenko, & Reimer (2000) includes a sophisticated 2-D model of the cosmic-ray, gas, and photon fields in the Galaxy, and includes hadronic interactions, electron bremsstrahlung and inverse Compton scattering of starlight. However, when using only known cosmic ray populations and spectra, this model is unable to account for the observed γ-ray spectrum. The spectrum above about 1 GeV is flatter than the prediction of pionic emission, so other sources seem to be required as well. Proposed explanations for this "GeV excess" include modifications to the proton spectrum, and additional inverse Compton radiation due to an extended halo of cosmic ray electrons (Strong, Moskalenko, & Reimer 2000). One of the main goals of this paper is to quantify the portion that can be pionic.

Information about the extragalactic component of diffuse γ-rays is more difficult to obtain, as one must first subtract the Galactic foreground, which is large at low–and possibly even high–Galactic latitudes. As we will see, the nature of the extragalactic spectrum depends on the method used to subtract the Galactic foreground. Different techniques have recently emerged, leading to different results for the shape and amplitude of the spectrum. Sreekumar et al. (1998) find a single power-law, while Strong, Moskalenko, & Reimer (2003) find a smaller but "convex" spectrum. In either case, no pion bump is seen.

Many astrophysical sites have been proposed to explain the extragalactic emission. These necessarily include "guaranteed" sources, namely, active (Stecker & Salamon 1996; Mukherjee & Chiang 1999) and normal (Pavlidou & Fields 2002) galaxies. These are the classes of objects which have been directly detected in nearby objects, but which would be unresolved when at large distances. Also, there is a growing consensus that the formation of large scale structures leads to shocks in the baryonic gas, and thus to particle acceleration. The resulting "cosmological cosmic rays" have recently become the subject of intense interest (Miniati et al. 2000; Loeb & Waxman 2000; Miniati 2002; Totani & Inoue 2002; Keshet, Waxman, Loeb, Springel, & Hernquist 2003; Berrington & Dermer 2003; Furlanetto & Loeb 2003). These can also contribute to the diffuse γ-background, and would have emission from both hadronic and inverse Compton processes.

Here we wish to find model-independent constraints on hadronic and thus pionic emission mechanisms. We choose to focus on this component because its detection would finally confirm observationally the theoretical expectation that the same astrophysical acceleration processes which give rise to non-thermal electrons (and associated synchrotron radiation) also give rise to non-thermal ions. Also, we wish to exploit the well-defined nature of the pion decay spectrum which allows us to make a roughly model-independent comparison with observations. Finally, since the same hadronic processes that produce neutral pions also produced charged pions and hence neutrinos, our limits will have implications for neutrino production as well.

2. Data

We will consider the Galactic and extragalactic emission in turn. For the Galactic spectrum, we adopt the EGRET data (Hunter et al. 1997) for the inner Galaxy ($300° < \ell < 60°$, $|b| \leq 10°$). We find that the flux density can be well-fit by a broken power law, with index -1.52 below 0.77 GeV, and index -2.25 above:

$$I_{\rm obs}(\epsilon) = \begin{cases} 4.66 \times 10^{-5} \epsilon_{\rm GeV}^{-1.52} \ {\rm cm}^{-2}{\rm s}^{-1}{\rm sr}^{-1}{\rm GeV}^{-1} & \epsilon_{\rm GeV} < 0.77 \\ 3.86 \times 10^{-5} \epsilon_{\rm GeV}^{-2.25} \ {\rm cm}^{-2}{\rm s}^{-1}{\rm sr}^{-1}{\rm GeV}^{-1} & \epsilon_{\rm GeV} > 0.77. \end{cases} \tag{1}$$

This simple fit somewhat overestimates the flux in the region within about ±100 MeV of the break, but this region will not strongly affect our results.

Although diffuse emission from the Galactic plane dominates the γ-ray sky, the emission is nonzero even at the Galactic poles, which suggests that there *is* an extragalactic component. However, it is already clear that careful subtraction will be crucial in obtaining the extragalactic gamma-ray spectrum. Several schemes have been proposed for subtraction of the Galactic foreground. The basic approach of the EGRET team (Sreekumar et al. 1998) is to correlate the γ-ray sky with tracers of Galactic γ-ray sources. The dominant source is the hydrogen column, itself derived from observations of neutral H at 21 cm, H_2 as traced by CO, and H II as probed by pulsar dispersion studies. The interstellar photon field, which is up-scattered by inverse Compton processes, is also estimated. Sreekumar et al. (1998) find evidence for a statistically significant isotropic component, with flux $I(> 100 \ {\rm MeV}) = (1.45 \pm 0.05) \times 10^{-5}$ photons cm^{-2} s^{-1} sr^{-1} and a spectrum consistent with a single power law of index 2.1 ± 0.03:

$$I_{\rm obs} = I_0 \left(\frac{E}{E_0}\right)^{-2.1 \pm 0.03} \tag{2}$$

where $E_0 = 0.451 {\rm GeV}$ and $I_0 = 7.32 \times 10^{-6} {\rm cm}^{-2}{\rm sr}^{-1}{\rm s}^{-1}{\rm GeV}^{-1}$.

Recently, Strong, Moskalenko, & Reimer (2003) have taken a different approach in subtracting the Galactic foreground, based on their sophisticated and detailed model of the spatial and energetic content of the Galaxy. They used the GALPROP model for cosmic ray propagation to predict

the Galactic component and give the new estimate of the extragalactic gamma-ray background (hereafter EGRB) from EGRET data. Strong, Moskalenko, & Reimer (2003) also find evidence for an EGRB, but with a different spectral shape, and in general a lower amplitude than that of Sreekumar et al. (1998). The Strong, Moskalenko, & Reimer (2003) Galactic foreground estimates also includes the Strong, Moskalenko, & Reimer (2000) estimate of the pionic contribution. This model-based constraint will serve as an important consistency check of our model-independent results. We used the least square method to fit their data with a cubic logarithmic function for the energy range 0.05-10 GeV:

$$\ln(I_{\mathrm{obs}}E^2) = -13.9357 - 0.0327\ln E + 0.1091(\ln E)^2 + 0.0101(\ln E)^3 \tag{3}$$

In this fit energy E is understood to be in the units of GeV and I in units of photons $\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}\,\mathrm{GeV}^{-1}$.

Indeed, the latest analysis of EGRET data done by Keshet, Waxman, & Loeb (2003) also implies that Galactic foreground was overestimated in previous work. They find that Galactic foreground in fact dominates the sky and that only an upper limit on the EGRB can be placed. However, Keshet, Waxman, & Loeb (2003) analysis did not contain spectral information which is why it is not further investigated in this paper. The data used in this paper along with the fits are shown in Fig.1 (Galactic component) and Fig.2 (EGRB).

3. A Simple Model for Pionic Gamma-Rays

The general expression for the γ-ray intensity spectrum at energy ϵ in a particular direction is given by the line-of-sight integral

$$I(\epsilon) = \frac{1}{4\pi}\int_{\mathrm{los}} q(\epsilon,\vec{r})\ ds = \frac{1}{4\pi}\int_{\mathrm{los}} \Gamma(\epsilon)n_H(\vec{r})\ ds \tag{4}$$

where we have ignored absorption and scattering processes which are negligible for $\epsilon \lesssim 20$ GeV (e.g., Madau & Phinney 1996; Salamon & Stecker 1998). In eq. (4) we write the γ-ray emissivity (production rate per unit volume) in terms of the local hydrogen density n_H and the production rate per H-atom (Stecker 1970; Dermer 1986, e.g.,)

$$\Gamma(\epsilon) = \int_{\epsilon+m_\pi^2/4\epsilon}^{\infty} \frac{dE_\pi}{\sqrt{E_\pi^2 - m_\pi^2}} \int dE_p \phi(E_p) \frac{d\sigma(E_p, E_\pi)}{dE_\pi} \tag{5}$$

Note that if the *shape* of the cosmic ray spectrum $\phi(E)$ is the same everywhere along the line of sight, then $I(\epsilon) = \Gamma(\epsilon)N_H$, where N_H is the hydrogen column density, and thus the shape of the observed γ-ray spectrum $I(\epsilon)$ is the same as that of the source $\Gamma(\epsilon)$. This is the case of interest to us.

The production rate Γ reflects the production and decay of neutral pions (with cross section σ) due to a cosmic ray flux spectrum ϕ. The shape of $\Gamma(\epsilon)$ has well-known properties that reflect the symmetry of the decay photons in the pion rest frame. As described in detail by Stecker

(1970, 1971), the underlying isotropic nature of the rest-frame emission and the cosmic-ray beam is encoded in the emissivity spectrum, whose only photon energy dependence is through the lower limit in eq. (5). This can be written as $\epsilon_0(\epsilon/\epsilon_0 + \epsilon_0/\epsilon)$ which clearly has a minimum at $\epsilon_0 = m_\pi/2$, and is invariant under $\epsilon/\epsilon_0 \to \epsilon_0/\epsilon$; these properties guarantee that the spectrum is peaked at $\epsilon_0 = 69$ MeV (the pion bump) and falls off symmetrically on a $\log F - \log \epsilon$ plot.

The other key property of emissivity is found in the isobar+fireball model, which provides a good fit to accelerator data (Dermer 1986). Namely, at high energies $\epsilon \gg m_\pi/2$, the emissivity goes to the power law $\Gamma(\epsilon) \sim \epsilon^{-\alpha_p}$ (and thus by symmetry it goes at low energies as $\epsilon^{+\alpha_p}$). This simple asymptotic power-law dependence is what allows us to constrain the pionic contribution of γ-ray spectra.

Note that the region of the spectrum immediately around the pion bump depends most sensitively on the details of the pion production cross section $d\sigma(E_p, E_\pi)/dE_\pi$ and thus on the shape of the proton spectrum $\phi_p(E)$ with which it is convolved. Consequently, a detection of the pion bump, and its width, would not only unambiguously identify a hadronic source, but would also constrain the spectrum of source particles. In this case, our constraints, which are based on the absence of a pion bump and the asymptotic behavior of the pion spectrum, become superfluous. We look forward to this obsolescence, due to the eventual detection of the pion bump by GLAST or its successors. But until then our results remain relevant.

A convenient semi-analytic fit to the pionic γ-ray source-function was recently presented by Pfrommer & Enßlin (2003). Using Dermer's model (Dermer 1986) for the production cross section, they arrive at the form:

$$\Gamma(\epsilon) = \xi^{2-\alpha_\gamma} \frac{n(r)_{p,\mathrm{CR}}}{\mathrm{GeV}} \frac{4}{3\alpha_\gamma} \left(\frac{m_{\pi^0}}{\mathrm{GeV}}\right)^{-\alpha_\gamma} \left[\left(\frac{2\epsilon}{m_{\pi^0}}\right)^{\delta_\gamma} + \left(\frac{2\epsilon}{m_{\pi^0}}\right)^{-\delta_\gamma}\right]^{-\alpha_\gamma/\delta_\gamma} \sigma_{pp} \tag{6}$$

The spectral index α_γ determines the shape parameter $\delta_\gamma = 0.14\alpha_\gamma^{-1.6} + 0.44$. The effective cross section σ_{pp} they modeled to the form $\sigma_{pp} = 32 \times (0.96 + e^{4.4-2.4\alpha_\gamma})$ mbarn. Following Dermer (1986) we take the pion multiplicity to be $\xi = 2$. The cosmic ray projectile number density is $n_p(r)$. This source function peaks at half the pion rest energy. In Dermer's model the γ-ray spectral index α_γ is equivalent to the cosmic ray spectral index i.e. $\alpha_\gamma = \alpha_p$ (Dermer 1986). Note that in our limits on the dimensionless *fraction* of observed emission that is due to pion decay, only the energy dependence (i.e., the *shape*) of the emissivity in eq. (6) is important.

For the case of extragalactic emission, these pionic γ-rays can come from different redshifts. Thus, for extragalactic origin eq. (4) becomes

$$I(\epsilon) = \frac{1}{H_0} \int dz \frac{n_{\mathrm{H,com}}(z)\Gamma[(1+z)\epsilon, z]}{(1+z)\mathcal{H}(z)} \tag{7}$$

where the dimensionless expansion rate $\mathcal{H}(z) = H(z)/H_0$ takes the form $\mathcal{H}(z) = \sqrt{\Omega_\mathrm{m}(1+z)^3 + \Omega_\Lambda}$ in a flat universe. The redshift dependence of the source-function Γ depends on the nature of the

emission site (galaxies, cosmological shocks, etc.). For purposes of illustration, we will use a single-redshift approx $n(z) = n_0 \delta(z - z_*)$. In this approximation different z_* amount to the shift of the pionic γ-ray flux in log-log plot. Thus in this simplistic view the form of the source-function would stay the same as in equation(6) but ϵ_γ would be substituted with $E_\gamma(1 + z)$ where E_γ is now the observed gamma-ray energy. Note that in this case, any pion bump would be redshifted, and thus would appear at energies $< m_{\pi^0}/2$. Thus it is clear that this feature is not apparent in the extragalactic spectrum, which is flat or even convex at these energies.

Of course, any realistic case will include contributions from a range of redshifts. However, one can view this distribution as an ensemble of delta functions, which will be an averaging over our simple cases, with a redshift-dependent weighting which scales as $(1 + z)^{-1} n_{\mathrm{H,com}}(z) \mathcal{H}(z)^{-1}$ (c.f. eq. 7).

4. Procedure

The main goal of this paper is to place a constraint to the maximal pionic contribution to diffuse gamma-ray flux based on the shape of the pionic spectrum, and fact that the pion bump is not observed. The way to obtain this upper limit is to see how much can we increase the pionic contribution by changing the parameters that it depends on so that it always stays at or below the observed values at all energies. The parameters that we change are the projectile and target number densities that enter in cosmic ray production of pions and the redshift from where we assume all pionic gamma rays originate. The condition of matching logarithmic slopes

$$\frac{d \log I_{\mathrm{obs}}(E)}{dE} = \frac{d \log I_{\pi^0}(E)}{dE} \tag{8}$$

of theoretical pionic gamma-ray flux and the fit to the observed gamma-ray flux guarantees that the ratio $I_{\pi^0}/I_{\mathrm{obs}}$ is extremized (and in fact maximized for the spectra we consider). Here $I_{\pi^0}(E) = n_H(\vec{r})\Gamma(E)$ and is given in units of $\mathrm{GeV}^{-1}\,\mathrm{s}^{-1}\,\mathrm{cm}^{-2}$. The energy which satisfies eq. (8) thus sets the values of our parameters that maximize pionic flux.

Since the energy of pionic gamma-rays depends on the redshift as stated in the previous section, the slope of this theoretical flux will be the following function of observed energy E and the redshift z:

$$\frac{d \log I_{\pi^0}}{d \log E} = -\alpha_\gamma \frac{(2E(1+z)/m_{\pi^0})^{\delta_\gamma} - (2E(1+z)/m_{\pi^0})^{-\delta_\gamma}}{(2E(1+z)/m_{\pi^0})^{\delta_\gamma} + (2E(1+z)/m_{\pi^0})^{-\delta_\gamma}} \tag{9}$$

Of course, for the Galactic spectrum we take $z = 0$.

The choice of α_γ depends on the origin of cosmic rays. In the case of Galactic cosmic rays we will be using the classic observed–i.e., *propagated*–value $\alpha_\gamma = 2.75$ (confirmed recently by, e.g., Boezio et al. 2003; Alcaraz et al. 2000; Sanuki et al. 2000). For extragalactic γ-rays, the sources are not known, but both blazars and shocks in cosmological structure formation have received considerable attention. For the case of blazars, it is not clear whether the emission is due to

hadronic or leptonic processes. Blazar γ-ray spectral indices have a distribution which averages give to a diffuse flux with index $\alpha_\gamma \sim 2.2$ Stecker & Salamon (1996); if the emission is pionic this would be the proton index as well. Also, it is well known that the spectral index of cosmic rays accelerated in fairly strong shocks is $\alpha \approx -2$ (Blandford & Eichler 1987; Jones & Ellison 1991) which is expected to be the case with the cosmic rays from structure formation. Although the spectrum of structure-formation cosmic rays is not very well known for this purpose we will adopt the value $\alpha_\gamma = 2.2$, which is near the strong-shock limiting value of 2, and consistent with the Galactic *source* value (see discussion in, e.g., Fields, Olive, Cassé, & Vangioni-Flam 2001), as well as that of blazars.

Now we have to match the slopes of the observed gamma-ray spectra to the slope of the theoretical pionic flux that was given in equation (9). This amounts to equating (9) with to the appropriate expressions for the spectra: eqs. (12) or (14) for extragalactic, and eq. (10) for Galactic. We then solve for $E_\gamma(z)$, where we put $z = 0$ for the Galactic case, and $z = z_*$ for the extragalactic case.

5.   Results

5.1.   Galactic Spectrum

As described in §2, we fit the EGRET data for the Galactic spectrum with a broken power-law (eq. 1), and we use the emissivity for a proton spectrum $\alpha_p = \alpha_\gamma = 2.75$. In order to set up an upper limit to the pionic contribution we match the low-energy index -1.52 to the slope of pionic γ-rays; fitting to the higher energy portion of the spectrum would lead to an unobserved excess in the low-energy portion. The logarithmic slope of galactic spectrum is then just

$$\frac{d \log I_{\mathrm{obs}}}{d \log E} = -1.52 \tag{10}$$

We now equate this with pionic slope qiven in eq. (9) and solve for $E_\gamma(z = 0)$. This sets up the maximal normalization to the pionic spectrum which is plotted in the Fig.1 along with the observed Galactic spectrum. Also plotted is the logarithmic residual function. After integration over energies up to 10 GeV we can finally obtain the maximal pionic fraction of the Galactic γ-ray flux based on the shape of the pion decay spectrum as well as the lack of as strong detection of the pion bump:

$$f_{\pi^0,\mathrm{MW}}(> \epsilon) = \frac{I_{\pi^0,\mathrm{max}}(> \epsilon)}{I_{\mathrm{obs}}(> \epsilon)} \tag{11}$$

where $I(> \epsilon) = \int_\epsilon I(E) dE$. We find pionic fraction to be $f_{\pi^0,\mathrm{MW}}(> 30\mathrm{MeV}) = 53\%$ and $f_{\pi^0,\mathrm{MW}}(> 200\mathrm{MeV}) = 81\%$. While this integral constraint provides a diagnostic of the hadronic "photon budget," we stress that the lesson of the residual plot in Fig. 1 is that the deficit is not at all uniform across energies, but is very large at both high and low energies.

5.2. Extragalactic Spectrum

By going through the slope-matching procedure described in the previous section we can fix the parameters that maximize the pionic contribution to the different extragalactic γ-ray spectra we consider. For the Sreekumar et al. (1998) spectrum (eq. 2), the logarithmic slope is just a constant

$$\frac{d \log I_{\rm obs}}{d \log E} = -2.1 \tag{12}$$

On the other hand, for (Strong, Moskalenko, & Reimer 2003, eq. 3), we have

$$\frac{d \ln I_{\rm obs}}{d \ln E} = -2 + \frac{d \ln(I_{\rm obs} E^2)}{d \ln E} \tag{13}$$

$$= -2.0327 + 0.2182 \ln E + 0.0305 (\ln E)^2 \tag{14}$$

In our simplistic picture we assume that all of the pionic γ-rays originated at a single redshift. Thus we go through this procedure for a set of redshifts ranging from $z = 0$ up to $z = 10$. Figure 2 shows our maximized pionic contribution for the two extreme redshifts, along with the fits to the observed γ-ray spectrum and the actual EGRET data points (Strong, Moskalenko, & Reimer 2003). We also present the residual, which is what it is left after pionic flux contribution is subtracted from the observed γ-ray spectrum. Here we see that for both EGRB spectra, the residual is large at low energies. However, the different shapes of the two EGRB candidate spectra lead to qualitatively different behavior at high energies ($\gtrsim 1$ GeV): the residual remains substantial ($\gtrsim$ a factor of 2) for the Strong, Moskalenko, & Reimer (2003) fit, suggesting the need for other component(s) to dominate both high and low energies. But for the Sreekumar et al. (1998) fit, the residual is small, and thus the pionic contribution can be dominant above 1 GeV. This difference highlights the current uncertainty of our knowledge of the EGRB spectrum (and even its existence, Keshet, Waxman, & Loeb 2003). Our analysis thus underscores the need for a secure determination of the Galactic foreground and the extragalactic background.

To finally obtain the upper limit for the γ-rays that originated from pion decay, we integrate pionic and the observed (for both fits) flux. Then the ratio of these energy-integrated fluxes is the maximal fraction of pionic γ-rays for a given redshift.

$$g(z) = \frac{\int_{E_0}^{10 {\rm GeV}} d\epsilon \, I_\pi(\epsilon, z)}{\int_{E_0}^{10 {\rm GeV}} d\epsilon \, I_{\rm obs}(\epsilon)} \tag{15}$$

In Fig. 3 we plot this ratio as a function of redshift for three different integration ranges and for both Strong, Moskalenko, & Reimer (2003) and Sreekumar et al. (1998) fits to EGRET data. Note that the results asymptotically approach unity. A glance at Figure 2 suggests the reason for this: the effect of increasing the emission redshift z_* to "slide" the pionic spectrum leftward, toward lower energies. As a result, the peak and low-energy falloff are redshifted out of the fit regime, and the remaining high-energy power-law tail of the pionic emission then provides a good fit to the observations.

6. Discussion

We have presented model-independent upper limits on hadronic γ-ray emission based on the shape of observed spectra and their lack of a pion bump. Above 100 MeV, one might expect that gamma-rays from π^0 decay should dominate the Galactic spectrum. However, we find that they can make only about 50% of total Galactic gamma-ray flux. From the shape of the residual function that is plotted in Fig.1 we can see that due to the break at 0.77 GeV, additional gamma-ray components are needed both above and below the ~ 250 MeV regime at which the pionic contribution can be maximized. The residual gamma-rays below this scale can possibly be accounted by bremsstrahlung and inverse Compton scattering (Strong, Moskalenko, & Reimer 2000). However, if the pionic component is near its maximum, there still is the need for at one more component of gamma-rays above ~ 300 MeV to account for the EGRET data; alternatively, a single process may be at work, but with pionic emission being sub-dominant at all energies. This model-independent result is in good agreement with the sophisticated analysis of different models by Strong, Moskalenko, & Reimer (2000). We also stress again that this analysis was based on the assumption that the pion bump is not observed. If a future γ-ray mission such as GLAST were to identify this feature that would allow us to set a more definite and stronger limit on the pionic fraction of diffuse gamma-rays.

The maximum pionic fraction of extragalactic γ-rays can be seen in Fig.3 for different methods of foreground subtraction. It can go from $20 - 90\%$, depending on the assumed redshift of cosmic ray origin, but also on method used in subtracting the Galactic foreground to obtain the EGRB. Namely, the Strong, Moskalenko, & Reimer (2003) fit gives the fraction of 20% for cosmic rays that originated at the present, up to about 70% for $z = 10$, and in both cases there is still a factor of $\gtrsim 2$ deficit of high-energy photons. On the other hand, the Sreekumar et al. (1998) fit implies a 20% pionic fraction for recent cosmic rays and about 90% for redshift 10 cosmic rays, with no significant deficit at high energies.. This large variation underscores the need for a robust procedure for determining the EGRB, and also emphasizes the power of a firm EGRB spectrum to constrain emission processes.

Our limits can be compared to the results of specific models. Miniati (2002) finds that the pionic component contributes about 30% of the total emission from structure-formation cosmic rays, with the balance arising from electron synchrotron emission. He in turn finds that the entire cosmic-ray component itself can be $\sim 20 - 30\%$ of the total (Sreekumar et al. 1998) observed background. Thus, the Miniati (2002) model finds that the pionic contribution is $\sim 6 - 10\%$ of the observed level, a fraction which would be larger if the smaller Strong, Moskalenko, & Reimer (2003) background were used. The work of Keshet, Waxman, Loeb, Springel, & Hernquist (2003) neglects pionic emission entirely, arguing that the synchrotron emission should dominate.

Of course, our extragalactic constraints reflect our simple single-redshift approximation for the origin of cosmic rays. More precise analysis should include some kind of averaging over the redshifts. Further progress first requires a detailed knowledge of the redshift evolution of sources and targets. On the other hand, if the "pionic bump" was observed in the EGRB spectrum by GLAST or other

future experiments then the position of its peak could immediately tell us something about the mean cosmic-ray flux. This information would then give us a better handle on the star-formation rate as a function of redshift.

Finally, we note that our constraints on photons of hadronic origin also have implications for neutrinos produced in the same processes, a connection which has been emphasized by Waxman & Bahcall (1999). This is of particular interest in the case of extragalactic neutrino emission, which may lead to high-energy ($E_\nu \gtrsim 1$ TeV) events observable by ICECUBE (Ahrens et al. 2004). Waxman & Bahcall (1999) use the energy density of ultra-high-energy ($\gtrsim 10^{19}$ eV) cosmic rays to derive limits on the high-energy cosmic neutrino flux. Furthermore, they find that the EGRB (in the power-law form of Sreekumar et al. (1998)) implies a neutrino flux above $\sim$ TeV which violates this limit by a factor of up to ~ 100, if the EGRB is of hadronic origin. Our limits on the pionic fraction of the EGRB are complementary to the Waxman & Bahcall (1999) result. Our constraints on the hadronic origin of the EGRB are weaker than their $\sim 1\%$ fraction, but are derived independently, based on the EGRB spectrum itself.

REFERENCES

Ahrens, J. et al. (ICECUBE2004, Astroparticle Physics, 20, 507

Alcaraz, J. et al. (AMS Collaboration) 2000, Physics Letters B, 490, 27

Berrington, R. C. & Dermer, C. D. 2003, ApJ, 594, 709

Blandford, R. & Eichler, D. 1987, Phys. Rep., 154, 1

Boezio, M. et al. 2003, Astroparticle Physics, 19, 583

Dermer, C. D. 1986, A&A, 157, 223

Fichtel, C. E., Kniffen, D. A., & Hartman, R. C. 1973, ApJ, 186, L99

Fields, B. D., Olive, K. A., Cassé, M., & Vangioni-Flam, E. 2001, A&A, 370, 623

Furlanetto, S., & Loeb, A. 2003, ApJ submitted (astro-ph/0312435)

Hunter, S. D. et al. 1997, ApJ, 481, 205

Jones, F. C. & Ellison, D. C. 1991, Space Science Reviews, 58, 259

Keshet, U., Waxman, E., Loeb, A., Springel, V., & Hernquist, L. 2002, ApJ, 585, 128

Keshet, U., Waxman, E., & Loeb, A. 2003, ApJ submitted (astro-ph/0306442)

Loeb, A., & Waxman, E. 2000, Nature, 405, 156

Madau, P. & Phinney, E. S. 1996, ApJ, 456, 124

Miniati, F. 2002, MNRAS, 337, 199

Miniati, F., Ryu, D., Kang, H., Jones, T. W., Cen, R., & Ostriker, J. P. 2000, ApJ, 542, 608

Mukherjee, R. & Chiang, J. 1999, Astroparticle Physics, 11, 213

Pavlidou, V. & Fields, B. D. 2002, ApJ, 575, L5

Pfrommer, C. & Enßlin, T. A. 2003, A&A, 407, L73

Salamon, M. H. & Stecker, F. W. 1998, ApJ, 493, 547

Sanuki, T. et al. 2000, ApJ, 545, 1135

Sreekumar, P. et al. 1998, ApJ, 494, 523

Stecker, F. W. 1970, Ap&SS, 6, 377

Stecker, F. W. 1971, Cosmic Gamma Rays, NASA SP-249

Stecker, F. W. & Salamon, M. H. 1996, ApJ, 464, 600

Strong, A. W., Moskalenko, I. V., & Reimer, O. 2000, ApJ, 537, 763

Strong, A. W., Moskalenko, I. V., & Reimer, O. 2003, to appear in the Proc. 28th International Cosmic Ray Conference (astro-ph/0306345)

Totani, T., & Inoue, S. 2002, Astropart. Phys., 17, 79
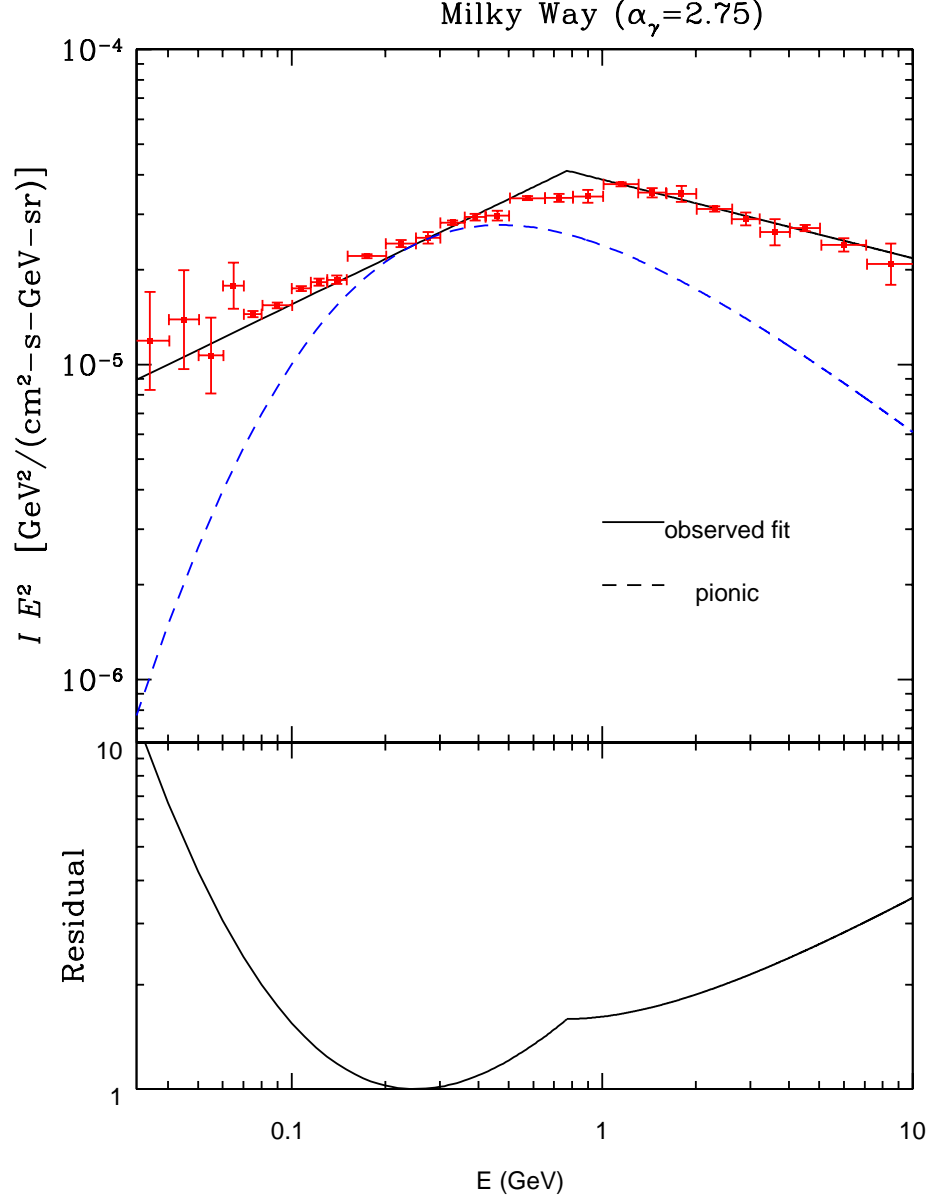
Waxman, E. & Bahcall, J. 1999, Phys. Rev. D, 59, 023002

Fig. 1.— In this figure we present the maximal pionic contribution to the Galactic γ-ray spectrum. EGRET data points are taken from Hunter et al. (1997). The lower panels represent the residual, that is, $\log[(FE^2)_{\rm obs}/(FE^2)_{\pi^0}] = \log(I_{\rm obs}/I_{\pi^0})$. Note that the kink at 0.77 GeV is unphysical and just due to the overshooting of the simple broken power-law fit.
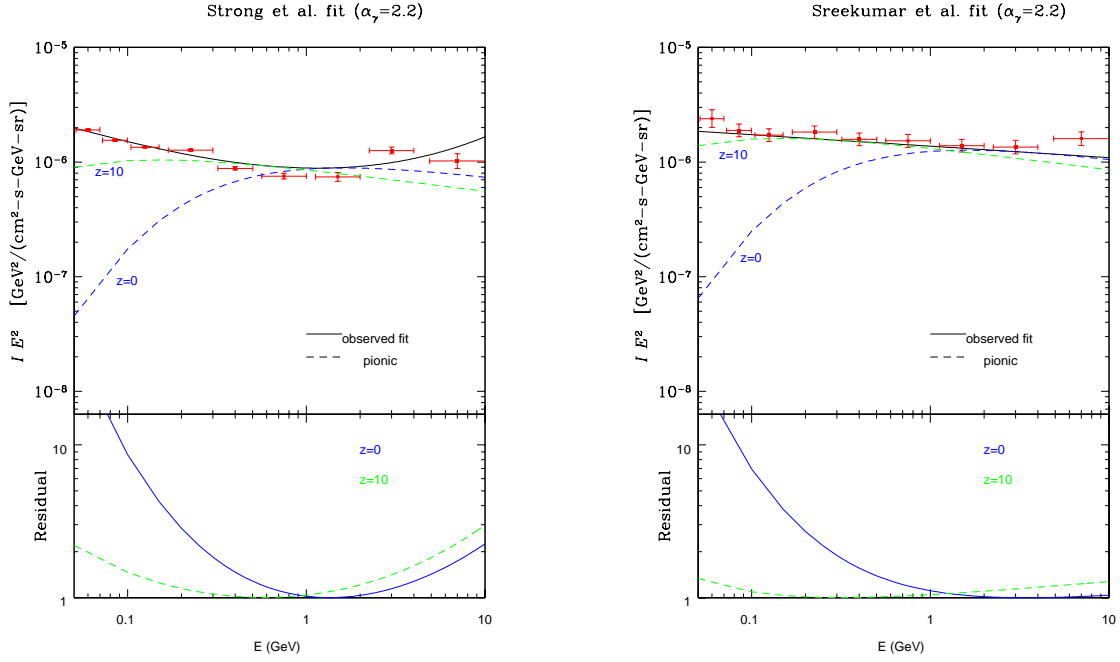
Fig. 2.— The maximal pionic contribution to the extragalactic γ-ray spectrum, computed by assuming that pionic γ-rays originated at a single redshift, namely at $z_* = 0$ and $z_* = 10$. EGRET data points for both fits taken from Strong, Moskalenko, & Reimer (2003). Lower panels represent the residual function as in Fig. 1.
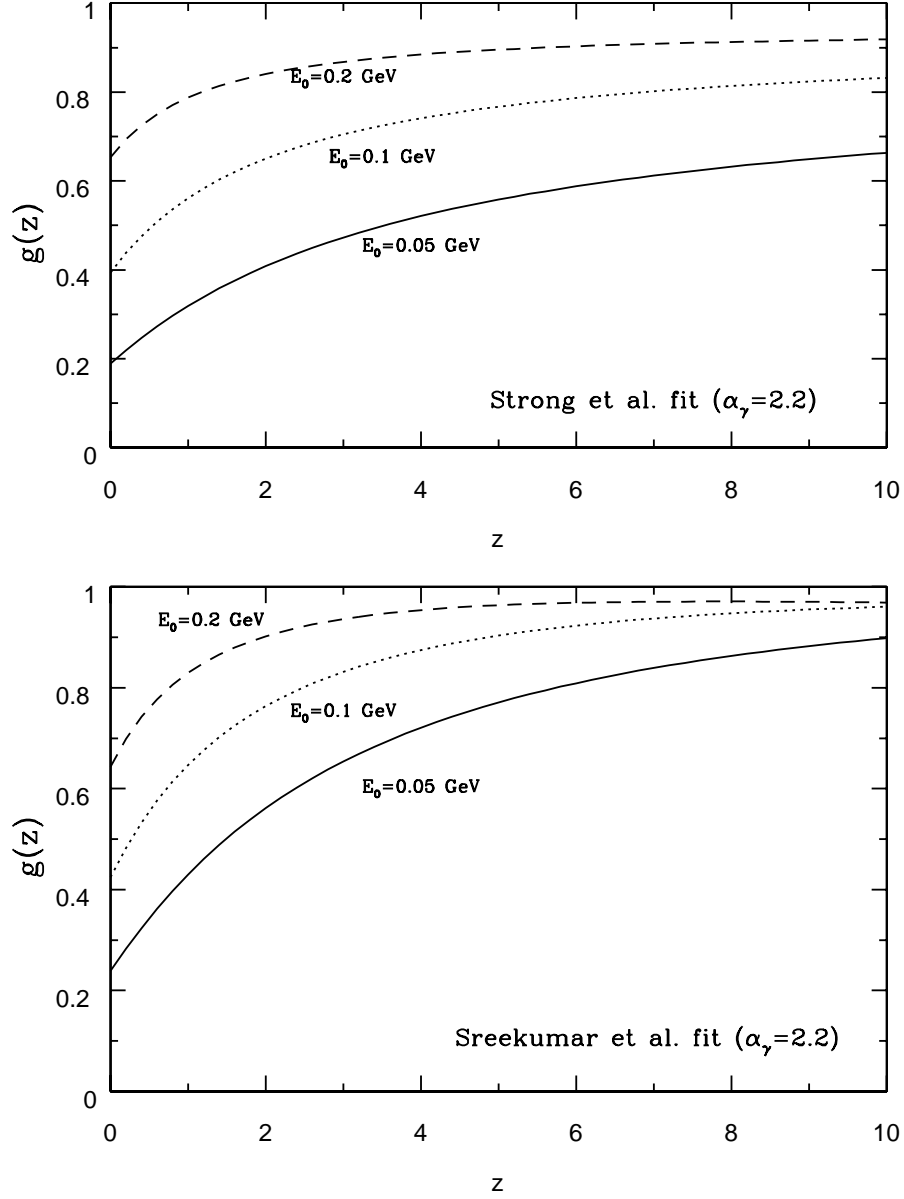
Fig. 3.— In this figure we see the maximal fraction of pionic energy-integrated flux. It is given as a function of the redshift of origin for the pionic γ-rays. Fluxes were integrated from E_0 up to 10 GeV.